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PARAMETRIC STUDY OF NEUTRONIC EFFECTS OF FUELED PERIPHERAL REFLECTORS IN GRAPHITE-CORE NUCLEAR ROCKET REACTORS

by Paul F. Herrmann

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1968

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PARAMETRIC STUDY OF NEUTRONIC EFFECTS OF FUELED PERIPHERAL REFLECTORS IN GRAPHITE-CORE NUCLEAR ROCKET REACTORS (U)

by Paul F. Herrmann

Lewis Research Center

SUMMARY

An improvement in specific impulse can be achieved by the topping-cycle propellant feed system, because it does not require the exhaust of spent, low-temperature turbine drive fluid (propellant) to space as in the present generation of nuclear rockets which employ a hot-bleed system. The topping-cycle system, however, requires a reflector-effluent propellant temperature that may only be attainable by fueling the reflector. The effects of the incorporation of fissionable material in the reflector on core radius and fuel concentration, total mass of uranium 235, reflector power fraction, and control-system worth are investigated using a neutron diffusion code in a five-fast, one-thermal energy-group structure.

Two configurations of fissionable material in the reflector are considered. In the first, uranium carbide (with the uranium enriched to 93 percent in the uranium 235 isotope) is distributed uniformly throughout the reflector. A severe uranium inventory penalty is incurred with this configuration for reflector moderator-to-fuel ratios less than about 400.

In the second configuration, an annulus consisting of a mixture of graphite and enriched uranium carbide is placed in the reflector. The void fraction of the fueled annulus is 0.2 or 0.3, the moderator-to-fuel ratio ranges from 50 to 200, the annulus thickness ranges from 1.27 to 3.81 centimeters, and the radial position of the annulus varies over a range of 7.62 centimeters. If the incorporation of the fueled annulus in the reflector is compensated by reducing the core fuel concentration for the optimum annulus position and a fixed (NERVA II) core radius, power fractions of from 0.14 to 0.34 are obtained, and the worth of the control system increases by $2 to $10 over the worth for the unmodified NERVA II reactor.

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INTRODUCTION

In the present generation of nuclear rockets, a turbine-pump combination is used to supply cryogenic propellant (liquid hydrogen) to the reactor core through the nozzle coolant tubes and reflector. The turbine is driven by hot propellant bled from the nozzle chamber after it has passed through the reactor core (hence, the term bleed turbine). The drive gas is then exhausted to space at a lower temperature with a resultant reduction in specific impulse. If, however, the propellant, which is effluent from the reflector, is at a temperature high enough to permit a turbine of moderate size and weight, the reflector effluent may be used to drive the turbine (called, in this kind of system, a topping turbine). All the propellant passes through the reactor core and main thrust nozzle, and there is no sacrifice of specific impulse.

A limiting parameter of such a system is, therefore, the temperature of the propellant as it leaves the reflector. The minimum temperature is limiting through the relation to turbine size. The maximum temperature is limited by the temperature capability of the reflector coolant passages and the turbine.

Because the small fraction (less than 5 percent) of total reactor power that appears in the reflector as gamma heating will probably not produce a high enough temperature, fueling the reflector has been proposed as a means of generating the required heat. This, however, may affect the dimensions of the reactor core, the core fuel concentration, and the worth of the peripheral, reflector-housed, rotating-drum control system that is used in these reactors.

The objective of this report is to determine what effect the incorporation of fuel into the reflector has on core radius and fuel concentration, mass of uranium 235 required, and the control system worth. The range of reflector variables (fuel concentration, void fraction, and, in the case of the fueled annuli, annulus thickness and position) was restricted to limit the reflector or fueled annulus power generation to about 50 percent of the total power generated (i.e., to limit the power fractions to 0.5 or less). This is consistent with a reactor effluent temperature of about 2800° K (5000° R), and a limiting reflector and turbine temperature of 1400° K (2500° R), which is slightly higher than present material temperature limits in the reflector and turbine. No attempt has been made to determine the feasibility of the fueled configurations with regard to heat transfer, fluid flow, or structural design.

In all the calculations in which the core or overall reactor radius is held constant, the NERVA II reactor will serve as a basic model from which the various fueled reflector configurations will depart and with which they will be compared in terms of core fuel concentration, total mass of uranium 235, and control system worth.

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METHODS OF CALCULATION

CODES

All machine calculations were carried out on the Lewis IBM 7094-II computer system. A one-dimensional, multigroup, multiregion diffusion code with group- and region-dependent extrapolation distances was used to solve the diffusion equations in cylindrical geometry for a five-fast, one-thermal energy-group structure. Energy-group boundaries are listed in table I.

Fast group macroscopic cross sections and diffusion coefficients were obtained from GAM II (ref. 1), which is a B_3 code for the calculation of slowing down spectra and associated multigroup constants. The thermal group parameters were obtained from the neutron thermalization code, TEMPEST (ref. 2).

CONTROL WORTH CALCULATIONS

A modification of a method of Charmatz (ref. 3) was used to calculate the worth of the control system. For the NERVA II reactor a curtain of boral 0.127 centimeters thick is placed in the reflector 1.905 centimeters from the inner surface of the reflector to simulate the geometry with the boral vanes full in. A simplified plan view of the explicit drum, and calculational model curtain geometry is shown in figure 1. The multiplication factor, k, is then calculated (Symbols are defined in appendix A.), and the curtain worth is determined from the difference between multiplication factors (with and without the curtain). The worth of the control system with the vanes full-in is obtained by taking the product of the curtain worth and the ratio of the total effective area of boral on the control drums to the curtain area (see appendix B). The effective area is the boral area calculated using a control drum radius that is larger than the actual radius by one thermal neutron mean free path in beryllium. This is done on the presumption that the capture effectiveness of the boral extends beyond the boral surface by that increment.

Because the reflector of the NERVA II reactor extends beyond the control drums toward the periphery as well as in the direction of the core, a vanes-out calculation is required. The curtain is placed in the reflector at a radius that corresponds to the outermost extent of the control drums. The control-system worth is then calculated from the worth of the curtain as before (using the larger curtain area representative of the curtain out configuration), and the net or swing control-system worth is obtained by subtracting the worth for the out configuration from that for the in configuration. The calculated value of net control-system worth was $9.50 for the 24-drum NERVA II system. Because the experimental value is approximately $9, the calculation was considered

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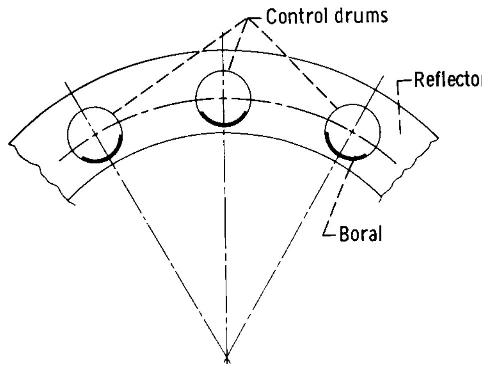
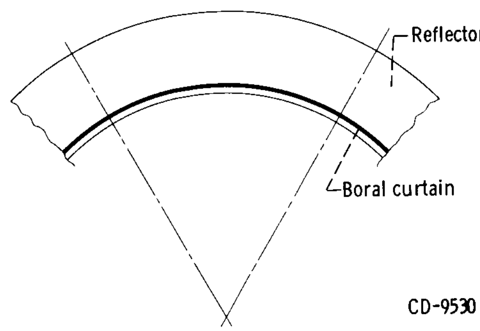


(a) Control drums.



(b) Calculational model (curtain).

Figure 1. - Partial plan view of reflector geometry.

to be sufficiently accurate to serve as a basis for comparison and to permit variations in the reflector in accordance with the introductory remarks.

DEFINITION OF MODELS

Before any changes were made in the basic configurations, two preliminary calculations were made from the basic NERVA II (ref. 4) and NRX-A (ref. 5) specifications (1) to determine the validity of using composite, volume-weighted average core compositions instead of several annular regions in which the uranium 235 (U^{235}) is radially zoned to flatten the radial power distribution, and (2) to determine the core heights consistent with a multiplication factor of 1.035. An excess multiplication Δk of 0.035 was chosen to permit compensation for the negative reactivity effects of temperature and the addition of structural components, cladding, control drums, and shimming.

Multiplication factors for the zoned and composite core NERVA II and NRX-A reactors using the physical core heights are listed as follows:

Reactor	Physical height of core, cm	Eigenvalues	
		Zoned	Composite
NERVA II	132.09	0.9964	0.9952
NRX-A	132.08	.9832	.9751

The difference between the zoned and composite calculations was about 0.1 percent for the NERVA II and 0.8 percent for the NRX-A, close enough for a parametric study to justify the use of the composite core approximation in all subsequent calculations. The core heights required for a multiplication factor of 1.035 are as follows:

Reactor	Core height for k_{eff} = 1.035, cm
NERVA II	153.00
NRX-A	189.73

The compositions and radii of the composite NERVA II and NRX-A cores are listed in table II. The compositions and radii of the regions external to the core are listed in table III. The thickness of the boral on the control drums was 0.127 centimeters, and the atom densities were

$$0.019 \times 10^{24} \text{ atoms/cm}^3$$

for aluminum and

$$0.0128 \times 10^{24} \text{ atoms/cm}^3$$

for boron 10.

RESULTS AND DISCUSSION

Two types of fueled reflectors were considered. In the first, uranium carbide (with the uranium enriched to 93 percent in the U^{235} isotope) was salted homogeneously into

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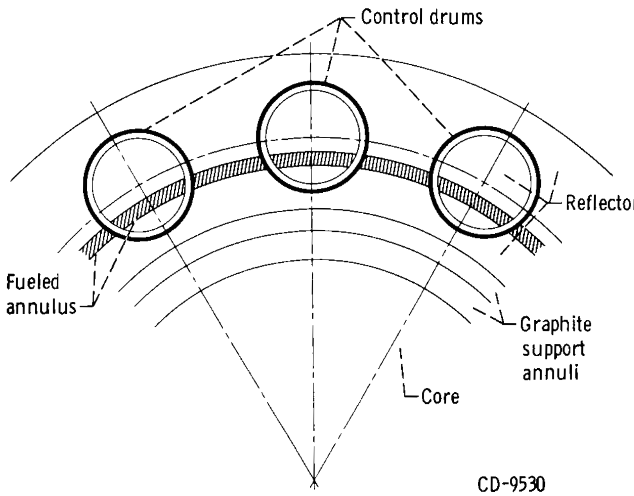

Figure 2. - Plan view of modified reflector geometry.

the reflector. In the second, a thin (1.27 to 3.81 cm thick) annulus of graphite and enriched uranium carbide (UC_2) was placed in the reflector (fig. 2). This annulus will hereinafter be referred to as a heater. To maintain the cylindrical continuity of the heater in accordance with the calculational model, the control drums must (because they occupy such a large fraction of the reflector circumference) be conceived as hollow cylindrical shells that rotate around a fixed core of reflector material in which a section of the heater is embedded.

In the first type, the reflector moderator-to-fuel ratio R_r, was defined by the equation

$$R_r = \frac{N_{Be} + N_c}{N_{U^{235}}}$$

where N is the atom density of the particular nuclide. In the second type, the moderator-to-fuel ratio of the fueled annulus R_h, was defined by the equation

$$R_h = \frac{N_c}{N_{U^{235}}}$$

In both cases, N_c included the carbon in the UC_2 molecule. The atom densities of beryllium, carbon, uranium 235, and uranium 238 in salted reflectors for all combinations of R_r and reflector void fraction, α_r, are listed in table IV. In the NERVA II reflector, chromium, iron, and nickel were omitted from the salted reflector atom density calcula-

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tions, and they were not included in the reflector composition for the reactor calculations. The atom densities of carbon and the two isotopes of uranium for all combinations of R_h and heater void fraction α_h are also shown. With the exception of the salted reflector compositions and the reflector modifications necessitated by the introduction of heaters, the compositions and structures (thickness of lateral support annuli, graphite barrel, and reflector) of the parts of the reactor assembly external to the core are those of the NERVA II or NRX-A reactors.

No attempt was made to correct the power fractions of the fueled reflectors for the azimuthal variations that would result from the presence of the control drums in the reflector.

NERVA II CLASS REACTORS

Incorporation of fuel in the reflector is compensated by dilution of fuel in the core. For these calculations, the atom densities of the nonfissile core materials were held constant, and the U^{235} atom density was calculated from N_c/R_c, where R_c is the core moderator-to-fuel ratio. Because the concentration of U^{235} in the unmodified NERVA II core is already quite low ($R_c = 167$), further dilution changes the concentrations of the nonfissile materials only very slightly. The ratio of U^{238} to U^{235} was held constant. The reflector and heater moderator-to-fuel ratios were varied from 50 to 200, and the void fractions were 0.2 and 0.3.

Salted Reflectors

The concentration of fuel in the core was varied to determine the value of R_c at which the core radius was equal to 71.45 centimeters (NERVA II) for an effective multiplication factor k_{eff} of 1.035. For all combinations of $R_r = 50$, 100, and 200, and $\alpha_r = 0.2$ and 0.3, the core radius was calculated for $R_c = 167$ (NERVA II), 200, 300, 400, and 500. For each combination of R_r and α_r, a curve was then drawn showing the variation of core radius with R_c. These are shown in figure 3. The value of R_c for the NERVA II core radius was defined for five of the six combinations. The values of R_c for a core radius of 71.45 centimeters, the U^{235} atom density in the core, the mass of U^{235} in the core and reflector, and the estimated (by interpolation between calculated points) reflector power fractions are listed in table V.

The U^{235} inventory data in table V represent an increase of 30 to 170 percent in the total mass of U^{235} over that used in the NERVA II core (about 279 kg). Reflector power fractions ranged from 0.32 to 0.52. At these reflector fuel loadings, the utilization of

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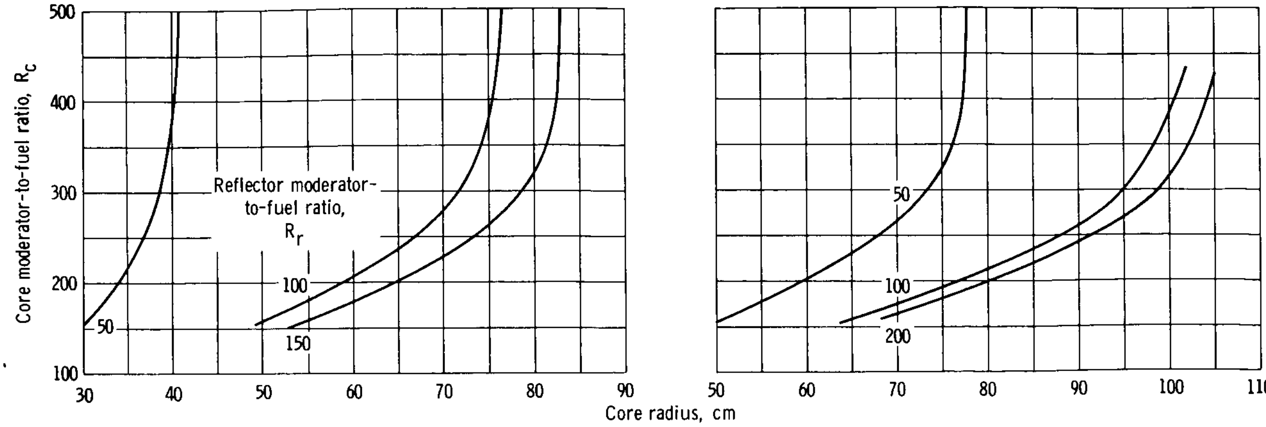

(a) Reflector void fraction, 0.2.

(b) Reflector void fraction, 0.3.

Figure 3. - Core fuel concentration as function of core radius for diluted NERVA II cores with salted reflectors.

fuel in the outer part of the reflector is very inefficient. Light reflector fuel loading ($R_r > 400$) or homogeneous distribution of fuel in only the inner part of the reflector may substantially reduce the inventory penalty, if the salted reflector concept should prove to have metallurgical, heat-transfer, or fabrication advantages over the heater (see the section, VARIABLE CORE RADIUS). However, either of these alternatives would involve a sacrifice of reflector power.

Heaters

As with the salted reflector configurations, the core fuel concentration was varied. But, in this case, the proper value of R_c for a fixed (NERVA II) overall reactor radius (the outer radius of the reflector) was determined. The choice of reflector thickness and the position of the heater in the reflector for which these calculations were made was based on the results discussed in the section VARIABLE CORE RADIUS. The thickness of beryllium in the reflector was held constant at 17.14 centimeters. The NERVA II thickness and the overall thickness of the reflector was increased in each case by an amount equal to the thickness of the heater. The increase in overall reflector thickness was compensated by allowing the core radius to be smaller by an equal increment, so that the outer radius of the reflector was unchanged. In all cases, there were 6.35 centimeters of beryllium between the outer graphite lateral support annulus and the inner cylindrical surface of the heater.

For all combinations of $R_h = 100$ and 200, $\alpha_h = 0.2$ and 0.3, and heater thicknesses of 1.27, 2.54, and 3.81 centimeters, the core radius was calculated for $R_c = 167$ (NERVA II), 200, 300, 400, and 500. A curve relating R_c and core radius was drawn

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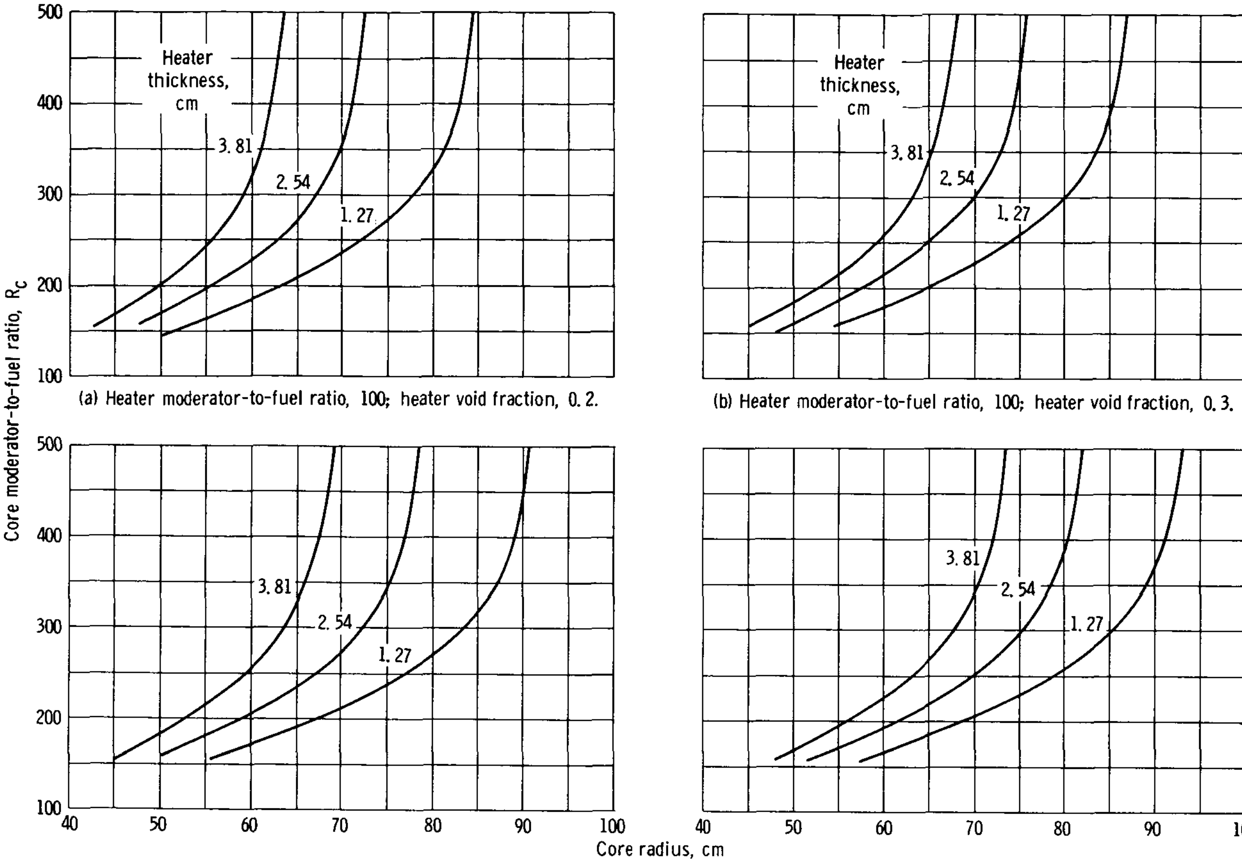

(a) Heater moderator-to-fuel ratio, 100; heater void fraction, 0.2.

(b) Heater moderator-to-fuel ratio, 100; heater void fraction, 0.3.

(c) Heater moderator-to-fuel ratio, 200; heater void fraction, 0.2.

(d) Heater moderator-to-fuel ratio, 200; heater void fraction, 0.3.

Figure 4. - Core fuel concentration as function of core radius for diluted NERVA II cores with heaters. Heater distance from graphite-beryllium interface, 6.35 centimeters.

(fig. 4), and the value of R_c corresponding to a core radius of 70.18, 68.91, or 67.64 centimeters (for a heater thickness of 1.27, 2.54, or 3.81 cm, respectively) was determined. The values of R_c, U^{235} core atom densities and inventories, and estimated heater power fractions for the 11 combinations of R_h, α_h, and heater thickness for which R_c was defined are listed in table VI.

Heater power fractions ranged from 0.14 to 0.34. Core moderator-to-fuel ratios ranged from 205 to 450, and the inventories of U^{235} were significantly less than that of NERVA II, with the largest only 229 kilograms for $R_h = 200$, $\alpha_h = 0.3$, and a heater thickness of 1.27 centimeters. The configurations with the thickest heaters produced the lowest inventories ranging down to 140 kilograms for $R_h = 200$, $\alpha_h = 0.2$, and a heater thickness of 3.81 centimeters.

The values of net control-system worth for these 11 cases were then determined, and they are listed in table VII. Comparison with the NERVA II control-system worth indicates an increase of \$2 to \$10. The largest increases are found for the thickest heaters.

VARIABLE CORE RADIUS

Using NERVA II and NRX-A core compositions, core radii were calculated for $K_{eff} = 1.035$ for various combinations of salted reflector and heater parameters. Core heights and reflector thicknesses are (except where modified by the presence of the heater) those of the NERVA II and NRX-A reactors. Consequently, there will be references in this section to a NERVA II case or an NRX-A case. However, when the core radius is varied (in this case made smaller), the reactor may no longer be considered a NERVA II or NRX-A in terms of power or thrust capability.

NERVA II

Salted reflectors. - The reflector moderator-to-fuel ratio was varied over a range of from 100 to 600 (for $\alpha_r = 0.2$) or 100 to 800 ($\alpha_r = 0.3$). The core radius for $k_{eff} = 1.035$, mass of U^{235} in the core and in the reflector, and the reflector power fraction are listed in table VIII for each combination of R_r and α_r. The variation of core radius and total U^{235} mass with R_r is shown in figure 5. Reflector power fractions ranged from 0.25 to 0.53. Over the range of R_r, core radii varied from 52 to 57 centimeters for $\alpha_r = 0.2$, and from 67.4 to 70.6 centimeters for $\alpha_r = 0.3$. For both values of α_r maxima occur for $150 < R < 200$. The radius decreases sharply for $R_r < 150$, but it decreases only slightly for $R_r > 200$. With the exception of those cases for which $\alpha_r = 0.2$ and $R_r > 340$, all require a considerably higher inventory of U^{235} than does the unmodified NERVA II, although the core radius of the unmodified NERVA II is larger.

Heaters. - An extensive series of calculations was made to survey the effect of heater thickness, fuel concentration, void fraction, and position in the reflector on core radius, U^{235} inventory, and heater power fraction. The effects were investigated at heater moderator-to-fuel ratios of 50, 100, and 200; heater void fractions of 0.2 and 0.3, thicknesses of 1.27, 2.54, and 3.81 centimeters; and positions in the reflector such that the thickness of beryllium between the outer graphite lateral support annulus and the inner cylindrical surface of the heater was 2.54, 6.35, and 10.16 centimeters. A fifth variable was the thickness of beryllium in the reflector. The results in table IX(a) are for an unchanged thickness of beryllium (17.14 cm). The overall reflector thickness is augmented by an amount equal to the thickness of the heater. Results of a representative

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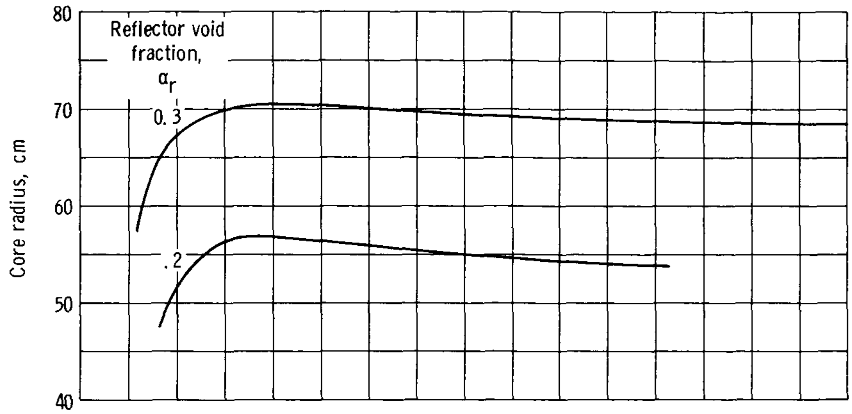
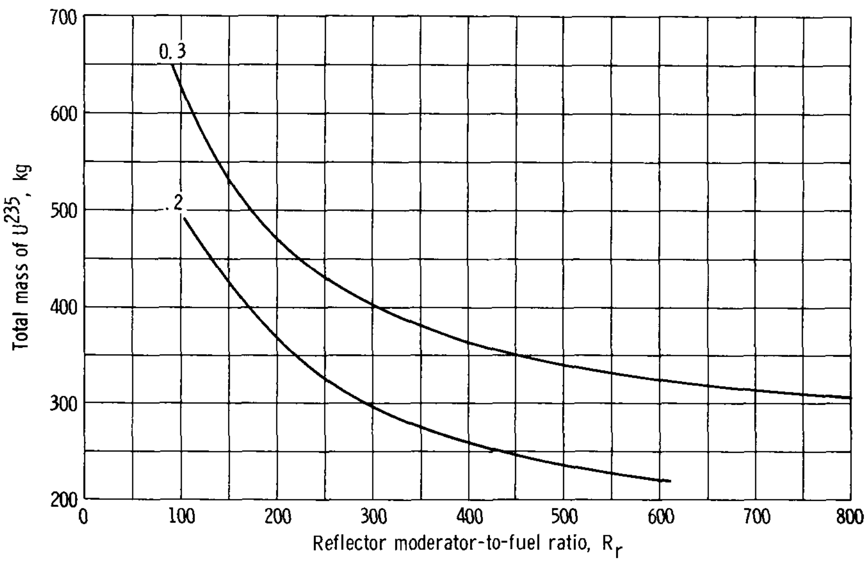


(a) Core radius as function of reflector moderator-to-fuel ratio.



(b) Mass of U^{235} as function of reflector moderator-to-fuel ratio.

Figure 5. - Effects of varying moderator-to-fuel ratio in salted reflectors. Core moderator-to-fuel ratio, 167; NERVA II material core compositions and reflector structure.

group of calculations, in which the overall reflector thickness was held constant and the thickness of beryllium was diminished by an amount equal to the thickness of the heater, are shown in table IX(b).

Differences between the results in tables IX(a) and (b) are immediately apparent. Whereas in table IX(a) the radius of the core decreased in response to increasing heater thickness, in table IX(b) the decreasing thickness of beryllium as the heater thickness increases produces an increase in core radius. The increase was 5 to 6 centimeters for a heater thickness of 1.27 centimeters, 10 to 12 centimeters for a thickness of 2.54 centimeters, and 15 to 20 centimeters for a thickness of 3.81 centimeters. The larger radii

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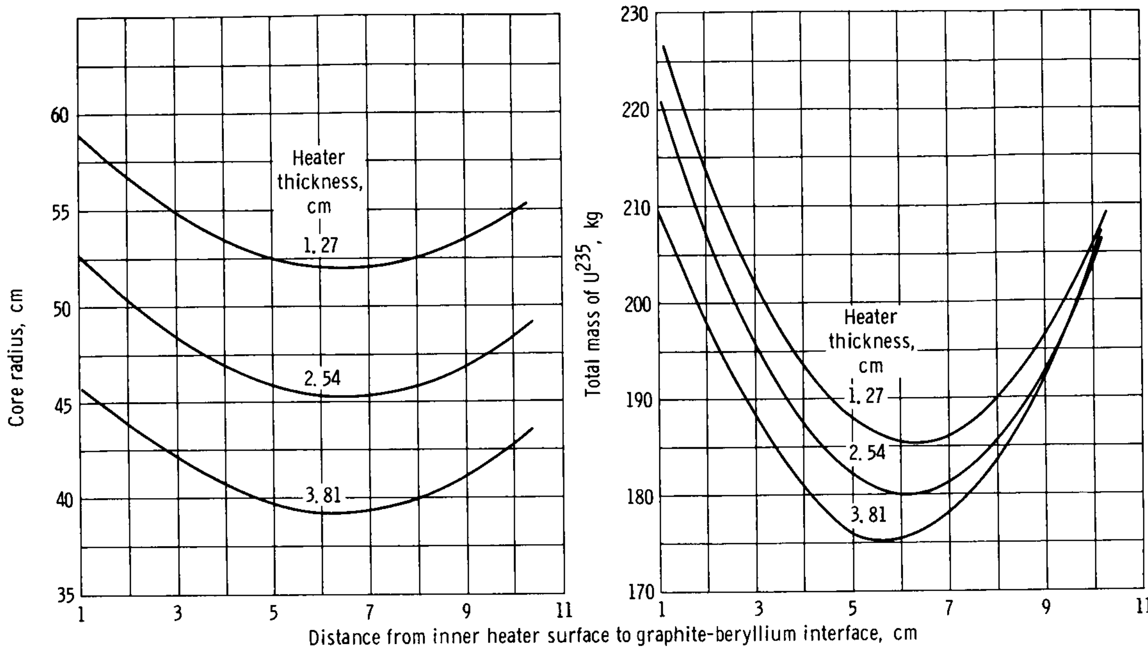
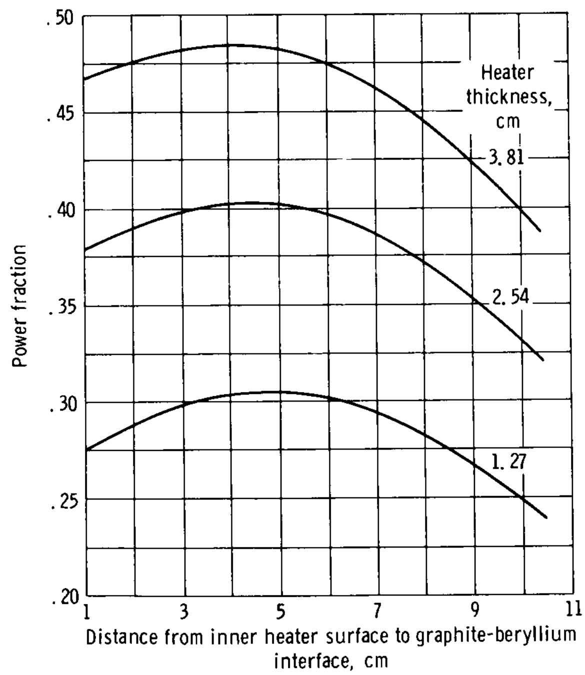


(a) Core radius as function of heater position.

(b) Total mass of U^{235} as function of heater position.



(c) Power fraction as function of heater position.

Figure 6. - Effects of varying heater position. Constant beryllium thickness; heater moderator-to-fuel ratio, 50; heater void fraction, 0.2; core moderator-to-fuel ratio, 167; NERVA II material compositions and reflector structure.

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resulted in larger U^{235} inventories in both the core and heater, but despite this, the heater power fractions were smaller.

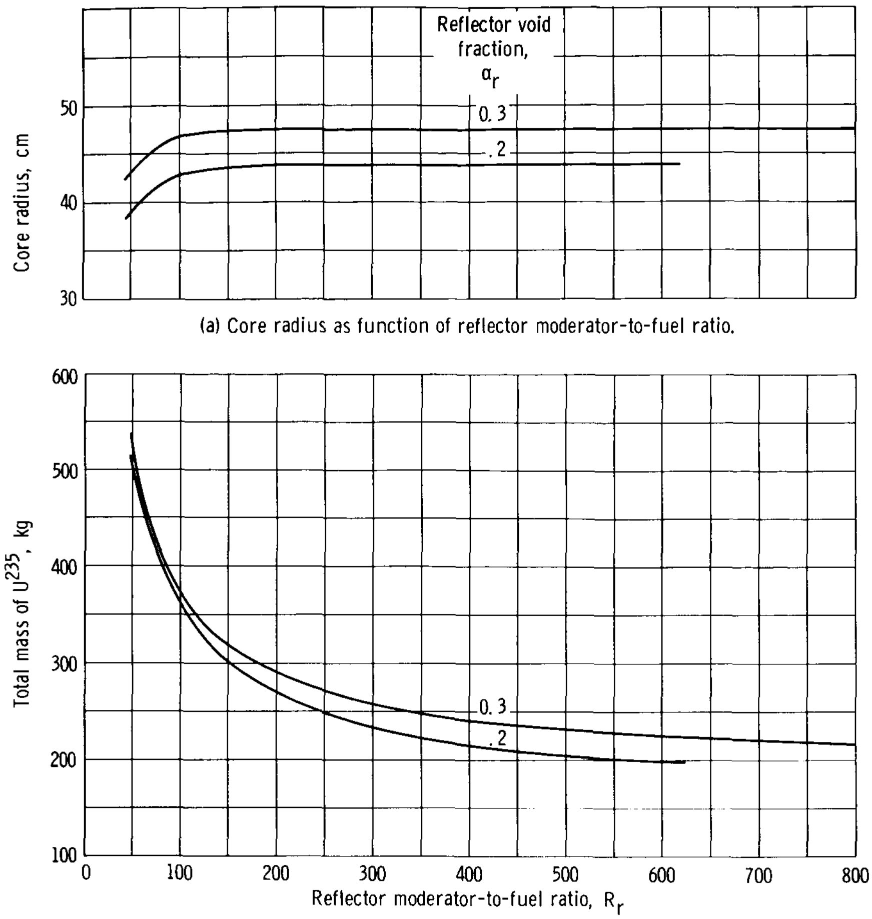
Table IX reveals a variation in core radius with the position of the heater in the reflector. For a fixed beryllium thickness of 17.4 centimeters, $R_h = 50$, and $\alpha_h = 0.2$, a series of calculations was made at each of the three heater thicknesses to determine the position that gives the smallest core radius and total U^{235} inventory, and the highest heater power fraction. The thickness of beryllium between the outer graphite lateral support annulus and the inner surface of the heater was varied from 1.27 to 10.16 centimeters. The results of these calculations are listed in table X(a). In figure 6, the core radius, total U^{235} mass, and heater power fraction are shown as a function of the heater position at each of the heater thicknesses. The optimum positions for all three variables are very nearly coincident. A separation of 5 to 6.5 centimeters offers the most favorable combination of parameters.

NRX-A

Salted reflectors. - A limited number of calculations were made for the NRX-A core composition. The reflector moderator to fuel ratio was varied over a range of from 50 to 600 (for $\alpha_r = 0.2$) or 50 to 800 (for $\alpha_r = 0.3$). The core radius, mass of U^{235} in the core and in the reflector, and the reflector power fraction are listed in table XI for each combination of R_r and α_r. The variation of core radius and total U^{235} mass with R_r is shown in figure 7. Reflector power fractions ranged from 0.16 to 0.48. Over the range of R_r, core radii ranged from 39.1 to 43.8 centimeters for $\alpha_r = 0.2$, and from 44.2 to 47.6 centimeters for $\alpha_r = 0.3$. The unmodified NRX-A core radius is 43.76 centimeters. In this range of core size the magnitude of the negative reactivity effect of increasing the reflector void fraction to 0.3 is larger than the positive reactivity effect of adding fuel to the reflector. Over the range of R_r from 50 to 600 or 800, there is no well-defined maximum; the variation of core radius is much smaller than it was for the NERVA II case.

Heaters. - Using a reflector with a fixed (NRX-A) thickness of beryllium, $R_h = 100$, and $\alpha_h = 0.2$, a series of calculations was made to determine the effect of heater position and thickness on the core radius, U^{235} inventory, and heater power fraction. The thickness of beryllium between the filler strip and the inner surface of the heater ranged from 1.27, 2.54, and 3.81 centimeters. The results are listed in table X(b). In figure 8 the core radius, total U^{235} inventory, and heater power fraction are shown as a function of heater position at each of the heater thicknesses.

There are several differences between these results and those for the NERVA II core composition. In the NERVA II case the optima for heater power fraction, core radius,

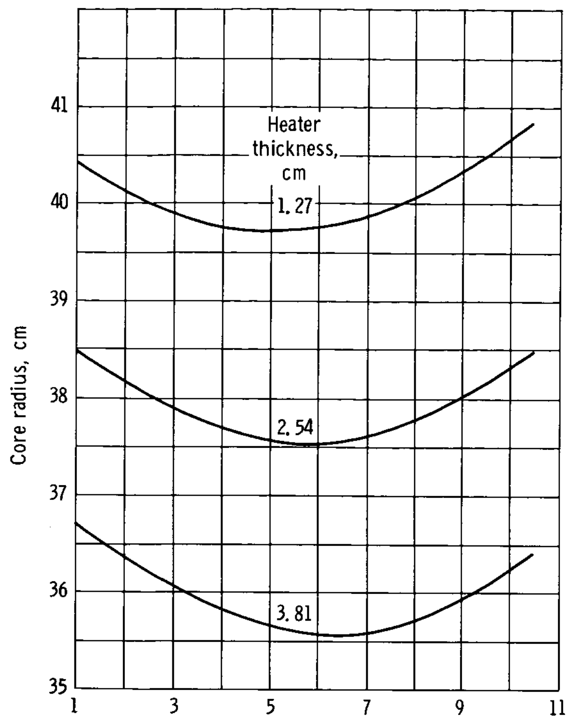


(a) Core radius as function of reflector moderator-to-fuel ratio.

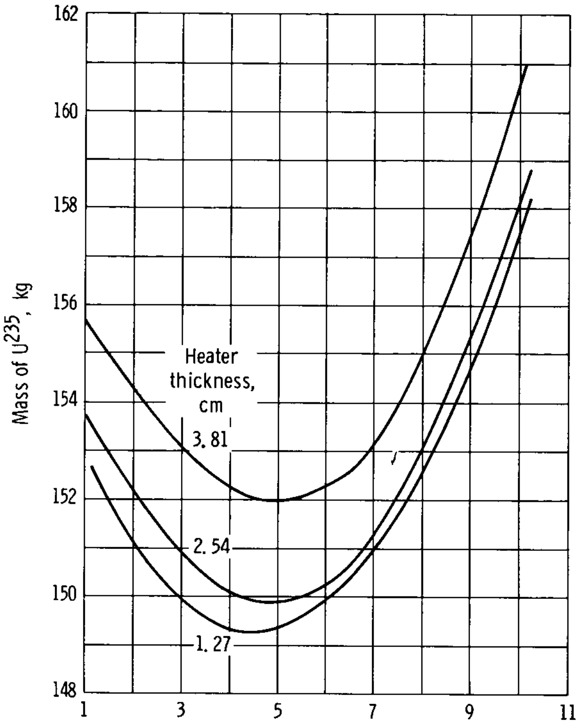
(b) Total mass of U^{235} as function of reflector moderator-to-fuel ratio.

Figure 7. - Effects of varying moderator-to-fuel ratio in salted reflectors. Core moderator-to-fuel ratio, 126; NRX-A material compositions and reflector structures.

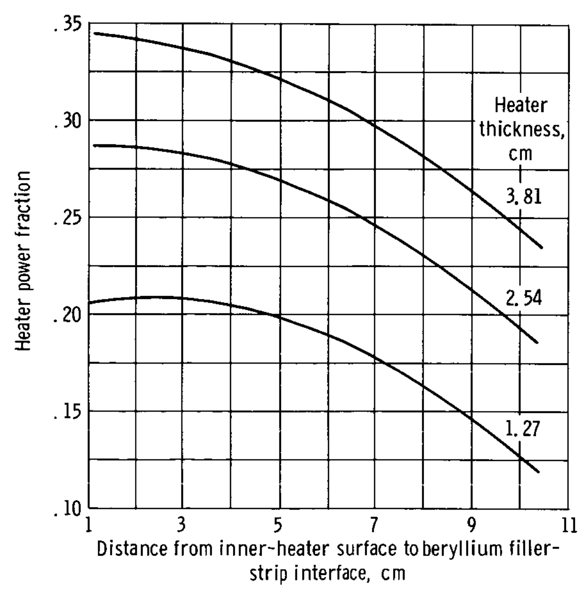
and U^{235} inventory were within a 2-centimeter range of radial position (from 4 to 6 cm away from the outer graphite lateral support annulus - reflector interface). With the NRX-A the core radius and U^{235} inventory optima are within 2 centimeters (from 4.5 to 6.5 cm from the filler strip - reflector interface), but the power fraction optimum is at or very close to the interface. The variation of core radius with either the heater position or thickness is much smaller for the NRX-A case than for the NERVA II case, despite the fact that the NRX-A results cover a wider range of heater position relative to the radial extent of the reflector. As a corollary, the fractional reduction in core radius which is affected by a heater of any given composition and thickness is smaller for the NRX-A core than for the NERVA II. Because the variation of the U^{235} core inventory is, then, also small, an increase in heater thickness results in an increase in the total U^{235} inventory. With the NERVA II core composition, the reduction in core radius was sufficient to overcompensate for the additional fuel incorporated in the reflector as the heater



(a) Core radius as function of heater position.



(b) Total mass of U^{235} as function of heater position.



(c) Heater power fraction as function of heater position.

Figure 8. - Effects of varying heater position. Constant beryllium thickness; heater moderator-to-fuel ratio, 100; heater void fraction, 0.2; core moderator-to-fuel ratio, 126; NRX-A material compositions and reflector structures.

thickness increased. Finally, the power fraction of a heater of given thickness was smaller when used with the NRX-A core than when used with the NERVA II, although the volume of the NRX-A heater represents a considerably larger fraction of the core volume.

CONCLUSIONS

By incorporating fissionable material into the peripheral reflector of a nuclear-rocket reactor, the temperature of the propellant can probably be increased by an amount sufficient to permit its use as a drive fluid for a topping turbine of moderate size. Two fueled reflector configurations were considered. In the first, the fuel (UC_2 enriched to 93 percent in U^{235}) was distributed uniformly throughout the reflector; in the second, a thin annulus of a mixture of graphite and enriched uranium carbide was placed in the reflector. The addition of fuel to the reflector was compensated either by diluting the concentration of fuel in the core while maintaining a constant core radius (relevant to a reactor with the power and thrust ratings of the unmodified NERVA II or NRX-A), or by permitting the radius of the core to decrease while maintaining a constant core fuel concentration (relevant, in general, to reactors with somewhat smaller power and thrust ratings).

In either case, a uranium inventory penalty serves as a strong argument against the use of a salted reflector (uniformly distributed fuel) for reflector moderator-to-fuel ratios less than about 400. However, if metallurgical, heat transfer, or fabrication considerations favor this concept, the inventory penalty could probably be eliminated or considerably reduced by using a configuration in which fuel is uniformly distributed throughout only the inner part of the reflector, by using more dilute reflector fuel concentrations, or by using some combination of the two. Any of these alternatives would result in a smaller reflector power fraction, and any reduction in reflector fuel concentration would mean a lower reflector effluent propellant temperature and a larger turbine. The first option (fuel zoning in the reflector) would probably be more difficult because of the need either to achieve adequate mixing of the warmer and cooler propellant streams as they leave the reflector or to divide the flow such that only the warmer gas is used to drive the turbine.

The alternative to the salted reflector concept is the heater, a thin annulus of graphite and uranium carbide placed in the reflector. Heater power fractions that ranged from 0.14 to 0.34 were obtained with an overall reactor radius of 93.6 centimeters (NERVA II). The core moderator-to-fuel ratios were 100 and 200, void fractions 0.2 and 0.3, and

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thicknesses 1.27, 2.54, and 3.81 centimeters. The total uranium 235 inventory ranged from 140 to 229 kilograms, compared with 279 kilograms in the NERVA II core. The increase in control-system worth for these configurations ranged from $2 to $10.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 13, 1967,
124-09-01-03-22.

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APPENDIX A

SYMBOLS

k multiplication factor

k_1 multiplication factor without curtain

k_2 multiplication factor with curtain

N atomic or molecular density, cm^{-3}

R moderator-to-fuel ratio or ratio of total number of moderator atoms to uranium 235 atoms

r_c core radius, cm

r_d control drum radius, cm

t_s support annulus thickness, cm

α void fraction

β delayed neutron fraction

Subscripts:

c core

eff effective

h heater

r reflector

[redacted]

[redacted]

APPENDIX B

CALCULATION OF CONTROL DRUM AND REACTIVITY WORTH

The boral annulus (or curtain) is inserted in the reflector, and the value of k_{eff} is calculated. The control worth of the boral annulus to the reactor is

$$\frac{k_1 - k_2}{k_1 k_2 \beta_{eff}}$$

where k_1 is the effective multiplication factor without control drums and k_2 is the effective multiplication factor from the calculation of k_{eff} with the boral annulus. An effective delayed neutron fraction of 0.0075 has been used throughout this report. The worth of a control drum is determined by means of a relation devised by Charmatz (ref. 3).

$$\text{Control drum worth} = \text{Curtain worth} \times \frac{\text{Effective area of boral on drum}}{\text{Area of curtain}}$$

The effective area of boral on the drum is

$$\frac{2\pi}{3}\,(r_d + 1.5)H$$

where $2\pi/3$ accounts for the 120° azimuthal extent of the boral coating on the drum, and 1.5 centimeters is the approximate thermal neutron mean free path in beryllium. The area of the curtain is $2\pi(r_c + t_s)H$.

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TABLE I. - ENERGY GROUP BOUNDARIES

Group	Energy range	
	eV	J
1	2.23×10^{6} to 14.9×10^{6}	3.57×10^{-13} to 2.39×10^{-12}
2	8.21×10^{5} to 2.23×10^{6}	1.315×10^{-13} to 3.57×10^{-13}
3	5.53×10^{3} to 8.21×10^{5}	8.86×10^{-16} to 1.315×10^{-13}
4	61.4 to 5.53×10^{3}	9.84×10^{-18} to 8.86×10^{-16}
5	0.414 to 61.4	6.63×10^{-20} to 9.84×10^{-18}
6	0 to 0.414	0 to 6.63×10^{-20}

TABLE II. - CORE ATOM DENSITIES

AND DIMENSIONS

[Core moderator-to-fuel ratio: NERVA II, 167; NRX-A, 126. Core radius: NERVA II, 71.45 cm; NRX-A, 43.76 cm.]

Element	NERVA II	NRX-A
	Atom density, at/cm^3	
Carbon	0.05642 $\times10^{24}$	0.065992 $\times10^{24}$
Chromium	.0001057	.0000654
Iron	.0001125	.0000931
Nickel	.0002453	.0001984
Niobium	.0006439	.0006912
U^{235}	.0003378	.0005232
U^{238}	.00002494	.00003892

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TABLE III. - ATOM DENSITIES AND DIMENSIONS OF REGIONS

EXTERNAL TO CORE

Reactor	Region	Outermost radius, cm	Element	Atom density, at/cm^3
NERVA II	Inner lateral support annulus	73.10	Carbon	0.08883×10^{24}
	Outer lateral support annulus	76.48	Carbon	0.0664×10^{24}
	Reflector	93.62	Beryllium	0.10238×10^{24}
			Carbon	.002289
			Aluminum	.00196
			Chromium	.00008659
			Iron	.000307
			Nickel	.0000389
NRX-A	Graphite barrel	45.24	Carbon	0.09694×10^{24}
	Lateral support annulus	50.97	Carbon	0.0584×10^{24}
			Aluminum	.00238
			Chromium	.00014
			Manganese	.0000139
			Iron	.00049
			Nickel	.0000619
	Reflector	62.70	Beryllium	0.112×10^{24}

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TABLE IV. - ATOM DENSITIES IN SALTED REFLECTORS AND HEATERS

(a) Salted relfectors

Reflector void fraction, α_r	Reflector moderator-to-fuel ratio, R_r	Beryllium	Carbon	U^{235}	U^{238}
		Atom densities, at/cm^3			
0.2	50	0.0899×10^{24}	0.00406×10^{24}	0.00188×10^{24}	0.000142×10^{24}
	100	.0944	.00208	.000965	.0000726
	150	.0960	.00140	.000647	.0000487
	200	.0968	.00106	.000490	.0000369
	250	.0973	.000847	.000391	.0000294
	300	.0976	.000707	.000327	.0000246
	400	.0980	.000532	.000246	.0000185
	500	.0982	.000426	.000197	.0000148
	600	.0984	.000355	.000164	.0000123
0.3	50	0.0787×10^{24}	0.00355×10^{24}	0.00165×10^{24}	0.000124×10^{24}
	100	.0826	.00182	.000844	.0000635
	150	.0840	.00123	.000567	.0000426
	200	.0847	.000924	.000428	.0000322
	250	.0851	.000741	.000342	.0000258
	400	.0857	.000465	.000215	.0000162
	600	.0861	.000311	.000144	.0000108
	800	.0863	.000233	.000108	.00000811

(b) Heaters

Heater void fraction, α_h	Heater moderator-to-fuel ratio, R_h	Carbon	U^{235}	U^{238}
		Atom densities, at/cm^3		
0.2	50	0.0709×10^{24}	0.00142×10^{24}	0.000107×10^{24}
	100	.0720	.000720	.0000542
	200	.0725	.000362	.0000273
0.3	50	0.0620×10^{24}	0.00124×10^{24}	0.0000934×10^{24}
	100	.0630	.000630	.0000474
	200	.0634	.000317	.0000239

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TABLE V. - PARAMETERS FOR SALTED NERVA II REFLECTORS AND DILUTED CORE FUEL CONCENTRATIONS

[Core radius, 71.45 cm.]

Reflector void fraction, α_r	Moderator-to-fuel ratio		U^{235} atom density, at/cm^3	Mass U^{235}, kg			Estimated reflector power fraction
	Reflector, R_r	Core, R_c		Core	Reflector	Total	
0.2	100	295	0.000191×10^{24}	157.9	455.5	613.4	0.490
	200	236	.000239	197.5	231.3	428.8	.416
0.3	50	282	0.000200×10^{24}	165.3	778.8	944.1	0.520
	100	181	.000312	257.9	398.4	656.3	.383
	200	171	.000330	272.7	202.0	474.7	.320

TABLE VI. - PARAMETERS FOR NERVA II HEATERS WITH DILUTED CORE FUEL CONCENTRATIONS

[Overall reactor radius, 93.6 cm.]

Heater			Core			Mass of U^{235}, kg			Estimated heater power fraction
Moderator-to-fuel ratio, R_h	Void fraction, α_h	Thickness, cm	Moderator-to-fuel ratio, R_c	Radius, cm	U^{235} atom density, at/cm^3	Core	Heater	Total	
100	0.2	1.27	237	70.18	0.000238	189.1	24.3	213.4	0.210
		2.54	333	68.91	.000169	129.4	48.2	177.6	.295
	0.3	1.27	224	70.18	0.000252	200.2	21.3	221.5	0.195
		2.54	285	68.91	.000198	151.6	42.2	193.8	.270
		3.81	450	67.64	.000125	92.2	62.8	155.0	.340
200	0.2	1.27	212	70.18	0.000266	211.3	12.2	223.5	0.150
		2.54	264	68.91	.000214	163.9	24.2	188.1	.230
		3.81	400	67.64	.000141	104.0	36.1	140.1	.300
	0.3	1.27	205	70.18	0.000275	218.5	10.7	229.2	0.140
		2.54	241	68.91	.000234	179.2	21.2	200.4	.210
		3.81	296	67.64	.000191	140.9	31.6	172.5	.265

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TABLE VII. - EFFECT OF HEATERS ON NERVA II CONTROL-SYSTEM WORTH

Heater			Core		Curtain in		Curtain out		Net control-system worth, $
Moderator-to-fuel ratio, R_h	Void fraction, α_h	Thickness, cm	Moderator-to-fuel ratio, R_c	Radius, cm	Effective multiplication factor, K_{eff}	Control-system worth, $	Effective multiplication factor, K_{eff}	Control-system worth, $	
100	0.2	1.27	237	70.18	0.91647	14.24	1.01725	1.64	12.60
		2.54	333	68.91	.89645	17.32	1.00843	2.50	14.82
	0.3	1.27	224	70.18	.92057	13.69	1.01817	1.55	12.14
		2.54	285	68.91	.90276	16.43	1.00777	2.57	13.86
		3.81	450	67.64	.86517	22.36	1.00261	3.12	19.24
200	0.2	1.27	212	70.18	.92317	13.35	1.01941	1.43	11.92
		2.54	264	68.91	.90119	16.63	1.00585	2.76	13.87
		3.81	400	67.64	.86499	22.39	.99820	3.56	18.83
	0.3	1.27	205	70.18	.92632	12.92	1.02025	1.35	11.57
		2.54	241	68.91	.90880	15.56	1.00832	2.52	13.04
		3.81	296	67.64	.87203	21.28	.99060	4.33	16.95

TABLE VIII. - EFFECTS OF REFLECTOR VOID FRACTION AND MODERATOR-TO-FUEL RATIO IN A SALTED REFLECTOR

[Core moderator-to-fuel ratio, 167.]

Reflector		Core radius, cm	Mass of U^{235}, kg			Reflector power fraction
Void fraction, α_r	Moderator-to-fuel ratio, R_r		Core	Heater	Total	
0.2	100	51.97	147.7	351.2	498.9	0.532
	150	56.46	174.3	251.6	425.9	.466
	200	56.92	177.2	191.8	369.0	.442
	250	56.50	174.6	152.1	326.7	.429
	300	56.07	171.9	126.4	298.3	.421
	400	55.06	165.8	93.7	259.5	.409
	500	54.38	161.7	74.4	236.1	.399
	600	53.94	159.1	61.5	220.6	.391
0.3	100	67.42	248.6	379.5	628.1	.392
	150	70.08	268.6	263.3	531.9	.344
	200	70.56	272.2	200.0	472.3	.322
	250	70.50	271.8	159.6	431.4	.309
	400	69.51	264.2	99.2	363.4	.288
	600	68.79	258.8	65.8	324.6	.269
	800	68.54	256.9	49.2	306.1	.254

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TABLE IX. - EFFECTS OF HEATER MODERATOR-TO-FUEL RATIO, VOID FRACTION, THICKNESS, AND POSITION

[Core moderator-to-fuel ratio, 167.]

(a) Constant beryllium thickness

Heater				Core radius, cm	Mass of U^{235}, kg			Heater power fraction
Moderator-to-fuel ratio, R_h	Void fraction, α_h	Thickness, cm	Distance from graphite-beryllium interface, cm		Core	Heater	Total	
50	0.2	1.27	2.54	55.68	169.6	37.3	206.9	0.295
			6.35	52.02	148.0	37.4	185.4	.300
			10.16	55.14	166.3	41.5	207.8	.246
		2.54	2.54	49.48	133.9	68.1	202.0	0.395
			6.35	45.31	112.3	67.7	180.0	.394
			10.16	48.69	129.7	76.1	205.8	.328
		3.81	2.54	42.97	101.0	91.9	192.9	0.480
			6.35	39.27	84.3	92.1	176.4	.471
			10.16	43.10	101.6	105.5	207.1	.394
	0.3	1.27	2.54	57.08	178.2	33.3	211.5	0.276
			6.35	53.25	155.1	33.3	188.4	.282
			10.16	56.30	173.4	36.8	210.2	.232
		2.54	2.54	51.75	146.5	61.8	208.3	0.368
			6.35	47.38	122.8	61.2	184.0	.370
			10.16	50.60	140.0	68.4	208.4	.307
		3.81	2.54	46.50	118.3	85.6	203.9	0.442
			6.35	42.37	98.2	85.2	183.4	.437
			10.16	45.78	114.6	96.2	210.8	.365
100	0.2	1.27	2.54	58.98	190.2	19.9	210.1	0.222
			6.35	55.71	169.7	20.1	189.8	.230
			10.16	58.48	187.0	22.0	209.0	.189
		2.54	2.54	53.64	157.4	37.0	194.4	0.314
			6.35	49.45	133.7	36.8	170.5	.321
			10.16	52.46	150.5	40.8	191.3	.266
		3.81	2.54	49.19	132.3	52.1	184.4	0.381
			6.35	44.61	108.8	51.4	160.2	.385
			10.16	47.60	123.9	57.5	181.4	.323

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TABLE IX. - Continued. EFFECTS OF HEATER MODERATOR-TO-FUEL RATIO, VOID FRACTION, THICKNESS, AND POSITION

[Core moderator-to-fuel ratio, 167.]

(a) Concluded. Constant beryllium thickness

Heater				Core radius, cm	Mass of U^{235}, kg			Heater power fraction
Moderator-to-fuel ratio, R_h	Void fraction, α_h	Thickness, cm	Distance from graphite-beryllium interface, cm		Core	Heater	Total	
100	0.3	1.27	2.54	60.13	197.7	17.7	215.4	0.205
			6.35	57.01	177.7	17.9	195.6	.213
			10.16	59.58	194.1	19.5	213.6	.175
		2.54	2.54	55.30	167.2	33.2	200.4	0.292
			6.35	51.33	144.1	33.2	177.3	.299
			10.16	53.98	159.4	36.5	195.9	.248
		3.81	2.54	51.83	146.9	47.6	194.5	0.352
			6.35	47.05	121.1	46.9	168.0	.358
			10.16	50.00	136.7	52.2	188.9	.299
200	0.2	1.27	2.54	61.47	206.7	10.4	217.1	0.157
			6.35	59.11	191.1	10.6	201.7	.165
			10.16	61.49	206.8	11.5	218.3	.135
		2.54	2.54	55.57	168.9	19.2	188.1	0.246
			6.35	52.27	149.4	19.3	168.7	.255
			10.16	55.49	168.4	21.4	189.8	.209
		3.81	2.54	51.40	144.5	27.2	171.7	0.310
			6.35	47.15	121.6	27.0	148.6	.320
			10.16	50.77	141.0	30.3	171.3	.264
	0.3	1.27	2.54	62.62	214.5	9.2	223.7	0.142
			6.35	60.41	199.6	9.4	209.0	.150
			10.16	62.53	213.8	10.2	224.0	.123
		2.54	2.54	57.62	181.6	17.3	198.9	0.224
			6.35	54.26	161.0	17.4	178.4	.233
			10.16	57.12	178.4	19.2	197.6	.191
		3.81	2.54	53.81	158.4	24.7	183.1	0.284
			6.35	50.00	136.7	24.7	161.4	.292
			10.16	52.87	152.9	27.3	180.2	.242

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TABLE IX. - Concluded. EFFECTS OF HEATER MODERATOR-TO-FUEL RATIO, VOID FRACTION, THICKNESS, AND POSITION

[Core moderator-to-fuel ratio, 167.]

(b) Constant overall reflector thickness

Heater				Core radius, cm	Mass of U^{235}, kg			Heater power fraction
Moderator-to-fuel ratio, R_h	Void fraction, α_h	Thickness, cm	Distance from graphite-beryllium interface, cm		Core	Heater	Total	
50	0.2	2.54	6.35	59.09	191.0	83.8	274.8	0.288
	0.3	2.54	6.35	60.93	203.0	75.1	278.1	0.269
100	0.2	1.27	6.35	61.44	206.4	21.8	228.2	0.196
		2.54	2.54	64.47	227.3	43.4	270.7	0.242
			6.35	62.05	210.6	44.2	254.8	.232
			10.16	64.27	225.9	47.8	273.7	.183
		3.81	6.35	63.86	223.0	68.5	291.5	0.239
	0.3	1.27	6.35	62.57	214.1	19.3	233.4	0.182
		2.54	2.54	66.08	238.8	38.8	277.6	0.224
			6.35	63.47	220.3	39.4	259.7	.216
			10.16	65.77	236.6	42.6	279.2	.169
		3.81	6.35	66.12	239.1	61.7	300.8	0.220
200	0.2	1.27	6.35	64.12	224.9	11.3	236.2	0.141
		2.54	2.54	65.68	235.9	22.2	258.1	0.189
			6.35	63.94	223.6	22.8	246.4	.183
			10.16	66.40	241.1	24.7	265.8	.141
		3.81	6.35	65.10	231.8	35.0	266.8	0.195
	0.3	1.27	2.54	65.06	231.5	10.0	241.5	0.128
		2.54	2.54	67.19	246.9	19.8	266.7	0.172
			6.35	65.50	234.6	20.4	255.0	.167
			10.16	67.56	249.6	21.9	271.5	.129
		3.81	6.35	67.38	248.3	31.5	279.8	0.177

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TABLE X. - HEATER POSITION EFFECTS

(a) Core moderator-to-fuel ratio, 167; heater moderator-to-fuel ratio, 50; void fraction, 0.2

Heater		Core radius, cm	Mass of U^{235}, kg			Heater power fraction
Thickness, cm	Distance from graphite-beryllium interface, cm		Core	Heater	Total	
1.27	1.27	58.36	186.3	38.1	224.4	0.279
	2.54	55.68	169.6	37.3	206.9	.295
	3.81	53.78	158.2	36.9	195.1	.303
	5.08	52.52	150.9	36.9	187.8	.305
	6.35	52.02	148.0	37.4	185.4	.300
	7.62	52.37	150.0	38.3	188.3	.287
	8.89	53.41	156.0	39.7	195.7	.269
	10.16	55.14	166.3	41.5	207.8	.246
2.54	1.27	52.04	148.1	69.6	217.7	0.382
	2.54	49.48	133.9	68.1	202.0	.395
	3.81	47.21	121.9	66.9	188.8	.402
	5.08	45.91	115.3	66.9	182.2	.402
	6.35	45.31	112.3	67.7	180.0	.394
	7.62	45.69	114.2	69.6	183.8	.378
	8.89	46.71	119.3	72.3	191.6	.356
	10.16	48.69	129.7	76.1	205.8	.328
3.81	1.27	45.35	112.5	93.8	206.3	0.470
	2.54	42.97	101.0	91.9	192.9	.480
	3.81	40.94	91.7	90.5	182.2	.485
	5.08	39.55	85.5	90.3	175.8	.483
	6.35	39.27	84.3	92.1	176.4	.471
	7.62	39.72	86.3	95.1	181.4	.452
	8.89	40.94	91.7	99.4	191.1	.427
	10.16	43.10	101.6	105.5	207.1	.394

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TABLE X. - Concluded. HEATER POSITION EFFECTS

(b) Core moderator-to-fuel ratio, 126; heater moderator-to-fuel ratio, 100; void fraction, 0.2

Heater		Core radius, cm	Mass of U^{235}, kg			Heater power fraction
Thickness, cm	Distance from graphite-beryllium interface, cm		Core	Heater	Total	
1.27	1.27	40.34	137.8	14.6	152.4	0.207
	2.54	40.00	135.5	14.9	150.4	.209
	3.81	39.80	134.2	15.2	149.4	.205
	5.08	39.74	133.8	15.6	149.4	.197
	6.35	39.86	134.6	16.0	150.6	.184
	7.62	40.00	135.5	16.4	151.9	.169
	8.89	40.29	137.5	16.9	154.4	.149
	10.16	40.72	140.5	17.4	157.9	.124
2.54	1.27	38.39	124.8	28.5	153.3	0.287
	2.54	38.03	122.5	29.1	151.6	.285
	3.81	37.73	120.6	29.6	150.2	.279
	5.08	37.57	119.6	30.3	149.9	.269
	6.35	37.56	119.5	31.0	150.5	.255
	7.62	37.70	120.4	31.9	152.3	.237
	8.89	37.99	122.3	32.8	155.1	.216
	10.16	38.36	124.7	33.8	158.5	.190
3.81	1.27	36.61	113.5	41.8	155.3	0.345
	2.54	36.21	111.1	42.5	153.6	.340
	3.81	35.87	109.0	43.4	152.4	.333
	5.08	35.65	107.7	44.3	152.0	.321
	6.35	35.57	107.2	45.3	152.5	.306
	7.62	35.65	107.7	46.5	154.2	.288
	8.89	35.90	109.2	47.9	157.1	.266
	10.16	36.29	111.6	49.4	161.0	.241

TABLE XI. - EFFECTS OF REFLECTOR VOID FRACTION AND MODERATOR-TO-FUEL RATIO IN SALTED REFLECTOR

[Core moderator-to-fuel ratio, 126.]

Reflector		Core radius, cm	Mass of U^{235}, kg			Reflector power fraction
Void fraction, α_r	Moderator-to-fuel ratio, R_r		Core	Heater	Total	
0.2	50	39.06	129.2	372.3	501.5	0.477
	100	42.77	155.0	204.6	359.6	.368
	150	43.59	161.0	139.2	300.2	.327
	200	43.78	162.4	105.8	268.2	.306
	300	43.80	162.5	70.6	233.1	.280
	400	43.77	162.3	53.1	215.4	.263
	500	43.77	162.3	42.5	204.8	.250
	600	43.77	162.3	35.4	197.7	.239
0.3	50	44.16	165.2	358.6	523.8	0.386
	100	46.70	184.7	187.5	372.2	.297
	150	47.25	189.1	129.9	319.0	.262
	200	47.41	190.4	98.3	288.7	.242
	400	47.50	191.1	49.5	240.6	.202
	600	47.53	191.4	33.1	224.5	.181
	800	47.60	191.9	24.9	216.8	.165

[redacted]

[redacted]

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